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AN ANALYSYS OF WEAR AND MECHANICAL AND TRIBOLOGICAL PROPERTIES OF HIGH-MANGANESE CAST STEEL HARDENED BY DIFFERENT METHODS

ANALIZA ZUŻYCIA ORAZ WŁASNOŚCI MECHANICZNYCH I TRIBOLOGICZNYCH WYSOKOMANGANOWEGO STALIWA UMACNIANEGO RÓŻNYMI METODAMI

Key words: Hadfield cast steel, wear, hardness, explosive hardening, static hardening, dynamic hardening.

Abstract: Properties of high manganese austenitic cast steel are not satisfactory; therefore, this material should be hardened. Currently, the commonly used method of hardening does not allow eliminating problems related to premature wear of railway frogs. Therefore, many studies have been carried out to find an alternative method to obtain improved wear resistance of such elements. The article presents an analysis of the mechanical and tribological properties of base and hardened, by different methods, high-manganese cast steel applied for turnouts. Tests were performed for three hardening methods: explosive, pressure-rolling, and dynamic impact. The results were compared with the properties of base material after saturation treatment. The conducted tests allowed the determination of hardness profiles of hardened surfaces, as well as the wear resistance and coefficient of friction, and the obtained results are very promising. Hardening by dynamic impact provided much better results in relation to presently used explosive hardening technology.

Słowa kluczowe: staliwo Hadfielda, zużycie, twardość, umacnianie wybuchowe, umacnianie statyczne, umacnianie dynamiczne.

Streszczenie: Właściwości austenitycznego wysokomanganowego staliwa nie są zadowalające, dlatego też materiał ten należy umacniać. Obecnie powszechnie stosowana metoda umacniania nie pozwala na wyeliminowanie problemów związanych z przedwczesnym zużyciem dziobów krzyżownic. W związku z tym wykonano badania mające na celu znalezienie alternatywnej metody dającej lepsze rezultaty. W pracy przeprowadzono analizę zużycia, właściwości mechanicznych oraz tribologicznych wysokomanganowego staliwa w wyniku zastosowania różnych technik umacniania. Podczas badań zastosowano metody umacniania wybuchowego, nagniatania naporowo-tocznego oraz dynamicznego. Wyniki porównano ze sobą oraz odniesiono je do właściwości materiału nieumocnionego, po przesycaniu. Badania pozwoliły na określenie twardości powierzchni, rozkładów twardości, wskaźnika zużycia objętościowego oraz współczynnika tarcia. Otrzymane wyniki badań są obiecujące. W wyniku nagniatania dynamicznego uzyskano lepsze wyniki w stosunku do badanego materiału umacnianego wybuchowo.

INTRODUCTION

High manganese cast steel is used for elements that require high hardness and abrasion resistance at high contact pressures for example, excavator buckets, ball mills, or rail turnout elements. The use of this cast steel with high manganese content (up to 14%) in the supersaturated state derives from its properties. It is characterized by high abrasive wear resistance (but only at high contact stresses), a resistance to brittle fracture, ductility, and high tensile and impact strength.

The main advantage is its high proneness to strengthening by strain hardening that leads to an increase of surface hardness. Despite that, it also has significant disadvantage, which is machining difficulty and problems with proper surface shaping of components

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made of it. The difficulty with machining is compensated by good castability; therefore, many elements with complicated shapes are produced by casting **[L. 1, 2]**. Currently, in the railway industry, high manganese cast steel (chemical composition according to WTWiO **[L. 10]**) is used in the production of some rail turnouts as a one-piece cast monoblocks (**Fig. 1**), inserts in a two-part switches (**Fig. 2**), and wheel passage zones in combined turnouts. The variety of railway frog construction results from their function, as well as the variation of applied loads that depend on the traffic on railway route and the speed limit on both straight and diverging tracks. These elements of railroads are the most loaded and exposed to wear during the train passage. Therefore, they are completely or partly made of Hadfield cast steel. This is due to the fact that, during passing through the frog, one wheel is in a contact with rail in a smaller surface than usual, while the second is simultaneously in a contact with inner side of the guard rail. Moreover, the unsupported wheel getting lower between the throat and the initial point of the frog and then strikes the frog causing its premature wear as a result of intense dynamic interactions. Despite the use of a lower position for the frog or higher wing rails, this problem has not been entirely eliminated, due to the insufficient stiffness of the wheel axle **[L. 3, 4]**. The properties of manganese cast steel cause that the exploitation process changes physical and mechanical properties of surface layer. In the initial period, the surface is strengthen, which leads to increases in hardness, while the other parameters, such as plasticity, decreases **[L. 2]**. However, before the surface layer of the frog is sufficiently strengthened, the most loaded elements are subjected to significant permanent deformations and evident pile-down on the frog edge, which should be removed by grinding.

Fig. 1. Monoblock frog of high-manganese austenitic cast steel [L. 5]

Rys. 1. Monoblok z wysokomanganowego staliwa austenitycznego **[L. 5]**

For this reason, a lot of research and experiments have been carried out recently, which have allowed the designing of various new constructions, materials, and technological solutions improving the functional properties of the discussed turnouts. However, the complexity of the problem causes that the solution for ensuring the required durability of turnouts is still being sought. The main aim is frog surface hardening to eliminate or at least reduce their permanent deformation and wear in the initial period of exploitation. One of the methods of the enhancement of surface layer properties of high manganese steel, which is currently the only one used in the railway industry, is explosive strengthening **[L. 6, 7]**. In this technology, the explosive material as SEMTEX 10SE tape is used to entirely cover the traded element previously sprinkled with sand. Detonation is caused by an electric detonator placed on one of the rail sides. Strengthening is a result of the shockwave effect. Two to three detonations are used to obtain the appropriate properties. Despite many advantages of this method and the strengthening of the surface layer, there are many discussions with respect to reproducibility on rail turnouts. The complicated shape of rail in both longitudinal and transversal cross-section makes problems with homogeneous strengthening of surface layer by the explosive method. This method unluckily brings the possibility of microcracks formation, which may cause later fatigue crack propagation during turnout operations. Moreover, it is still unclear how much explosive material should be placed in order to obtain a specific hardness of surface while maintaining the appropriate roughness. It is difficult to control this process, which means that repeatability of obtained surface layer properties is unsatisfactory. Subsequent mechanical methods of a surface layer of manganese cast steel formation are based on cold-work hardening. One of them is static-rolling burnishing, while the other is dynamic hammering **[L. 8, 9]**. Both of them could be used to strengthen turnout elements; therefore, the results of research aimed to apply them in this field are presented in this publication. The static burnishing is based on the interaction of a rotating tool, as a pressed roller with adequate load, with the treated element. The tool simultaneously reduces surface roughness. The other utilizes subsequent impacts of a stationary tool, which, at the appropriate feed rate, strengthens the surface layer along the entire length of the element. Optimal process parameters, such as, feed, frequency, and load derive from impact energy and should allow avoiding surface waviness and surface flaking due to excessive plastic deformation. Static strengthening allows one to obtain better mechanical properties, e.g., roughness; however, the thickness of hardened layer is lower than after dynamic strengthening.

In this work, the effect of strengthening by the explosive method with one and two explosions as well as static rolling and dynamic burnishing on mechanical and tribological properties of surface layers on Hadfield cast steel, used for the production of some types of frogs in rail turnouts, was analysed. The purpose of the research program is developing the technology that allows one to obtain the desired properties of the surface layer on manganese frogs before their exploitation. Achieving this goal would eliminate problems related to plastic deformation of frogs and their premature wear, which is currently associated with the necessity of an additional grinding operation.

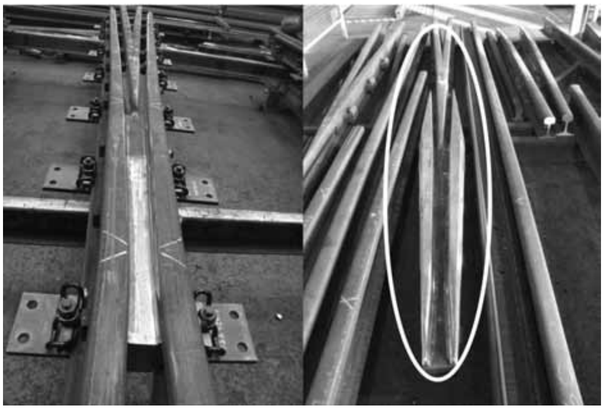

Fig. 2. Two-parts insert type frog of turnout [L. 5]
Rys. 2. Krzyżownica dwuczęściowa typu insert **[L. 5]**

TESTED MATERIAL AND METHODS

The cuboid samples made of high-manganese manganese steel with dimensions 25 × 25 × 10 (width × length × height) were subjected to tests. The chemical composition of the raw material is given in WTWiO **[L. 10]**. Samples were hardened by explosive strengthening with one or two explosions, static rolling, and dynamic burnishing and compared with untreated material. For the explosive method, SEMTEX 10SE tape was used. The static cold-work process was performed on a horizontal planer using a ball bearing as a working tool. Strengthening was carried out at 45 mm/min feed and a constant deformation of 0.03 mm continuously measured during the treatment. Dynamic strengthening was carried out on a milling machine. The working tool was a spindle fastened in a hammer drill and then mounted in the milling machine holder. Process parameters were 40 mm/min feed, 2620 strokes/min, and 3.8J stroke energy. The tribological properties were determined with a ball-on-disc tribotester. During the tests the following were used: 6 mm diameter Al_2O_3 ball, 5N normal load, 15–20 mm wear track radius, n = 120 rotations per minute, and N = 20.000 cycles. Wear resistance as wear index after wear track profile measurements were calculated from Equation (1) **[L. 11]**:

$$W_v = \frac{V}{F_n \cdot s}\left[\frac{mm^3}{Nm}\right] \tag{1}$$

where: V – volume of worn material,
F_n – normal load,
s – wear track length.

A contact profilometer was used to measure of wear track profiles. The obtained results allowed distinguishing the prevailing form of wear (grooving, rubbing, adhesive). Its character was determined based on pile-ups to groove areas ratios. The higher the value of this ratio, the higher is the amount of grooving. Abrasive wear is dominant when the ratio is lower than 0.1. Besides the tribological properties, the hardnesses of surface layers were also measured. Tests were carried out using the Brinell method to determine HB, due to the requirerments indicated in the standard **[L. 12]** of the critical and minimal 321 HB hardness of frog surfaces. The hardness profiles were also measured on rail cross-sections to find the thickness of the hardened layer. Low load indentations (F_N=100 mN) were performed according to the instrumental indentation method. During the tests, the load was increasing linearly with a 200 mN/min loading speed up to the maximum value of 100 mN, and then it remained constant for 5 seconds before unloading with the same speed as for loading. Microhardness was calculated from Equation (2) **[L. 10]**:

$$\mu HV = \frac{F_N}{A_C} \tag{2}$$

where: F_N – maximal normal load,
A_C – contact area of indenter and tested material.

The first indentation was done at a 30 μm distance from the rail surface, and then subsequent tests were 50 μm from the previous test up to 1 mm distance from the surface. These results were compared to the untreated Hadfield cast steel reference sample to indicate the most effective strengthening method.

TESTS RESULTS

During tribological tests, the friction force was recorded, and the resulting mean values of calculated coefficients of friction CoF are shown in **Fig. 3**, while the evolution of this parameter during the whole test duration is shown in **Fig. 4**. Test results showed that the friction coefficient of unhardened Hadfield cast steel was 0.93. The lowest value, 0.79, was obtained for the sample after two explosions, and the highest value, 1.15, was obtained for samples after one explosion. High-manganese cast steel in the rail industry is usually strengthened by two explosions, and one can find that this second explosion caused a CoF reduction by 46%. In relation to the reference cast steel, it decreases by 15%. The static burnishing caused a slight increase of friction CoF = = 0.98, while the dynamic strengthening reduced the coefficient of friction to 0.89, which is only 4% lower than that of the untreated surface. For the reference sample, CoF fluctuated in the initial test period and then stabilized after about 10,000 cycles. In the case of a single explosion, the friction coefficient is the most irregular and deviates from the all others. Throughout the whole test it was increasing, which may indicate the formation of adhesive joints. The second explosion reduces this problem and gives the lower value of CoF. Up to about 5,000 cycles, it fluctuates and then stabilizes at value similar to the sample after dynamic hardening and remains constant until the end of the test. It should be pointed out that treatment with two explosions results in the lowest CoF value.

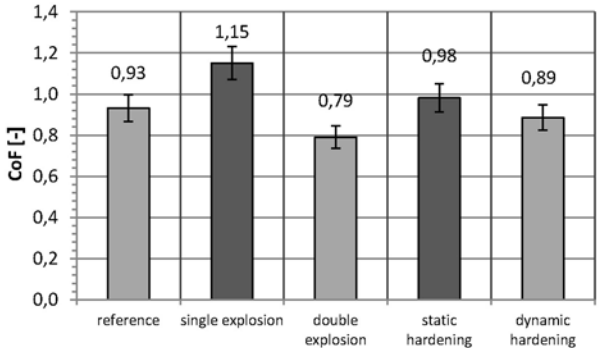

Fig. 3. **Average values of friction coefficient of Hadfield cast steel**

Rys. 3. Średnie wartości współczynnika tarcia staliwa Hadfielda

In the case of the statically burnished sample, up to about 5,000 cycles, it increases, and then it slightly decreases. The friction coefficient remains constant after 12,000 cycles, and it is similar to reference cast steel sample. For the dynamically hardened surface, CoF increases to about 11,000 cycles, and then it stabilizes at value slightly lower than for untreated steel. The wear index values are shown in **Fig. 5**. Based on microscopic observations and the shape of wear profiles of all Hadfield cast steel samples treated in this experiment, it could be stated that the main wear mechanism is abrasion. Some plastic deformation on wear track profiles was noticed for raw manganese steel. However, the ratio of pile-up areas to grooves did not exceed the value of 0.15, and the wear index is equal to $1.2 \cdot 10^{-3} \frac{mm^3}{Nm}$. The lowest value ($0.42 \cdot 10^{-3} \frac{mm^3}{Nm}$) of the wear index after dynamic burnishing was 75% lower than the reference material. In the case of explosive strengthening, two explosions reduced wear by 41% to $0.71 \cdot 10^{-3} \frac{mm^3}{Nm}$. But it is 41% higher wear than the sample with dynamic strengthening, while a single explosion caused increase of wear resistance by 22%. This confirms that the second explosion used in rail surface hardening is necessary. Likewise, the static strengthening also allowed reducing the wear index to $0.97 \cdot 10^{-3} \frac{mm^3}{Nm}$, which is 19% lower than for raw material. However, it is 57% and 27% higher compared to dynamic strengthening and two explosions, respectively. The results of HB surface hardness measurements are shown in **Fig. 6**. The hardness of reference material 214 HB agree with requirements in WTWiO. All strengthening methods caused a significant increase in surface hardness. Similar to results presented in **[L. 6, 7]**, the hardness increase by the explosive method is higher after the first explosion. The measured hardness 481 HB is 2.25 times higher than the reference material. The second explosion caused a further increase up to 552 HB, and, in relation to first explosion, the increase is only 15%. Referring this result to the raw material, the hardness increased about 2.6 times.

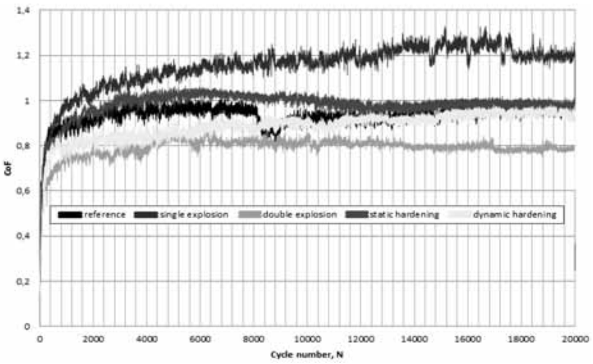

Fig. 4. **Evolution of friction coefficient of hardened and base Hadfield cast steel**

Rys. 4. Przebieg współczynnika tarcia umocnionego i nieumocnionego staliwa Hadfielda

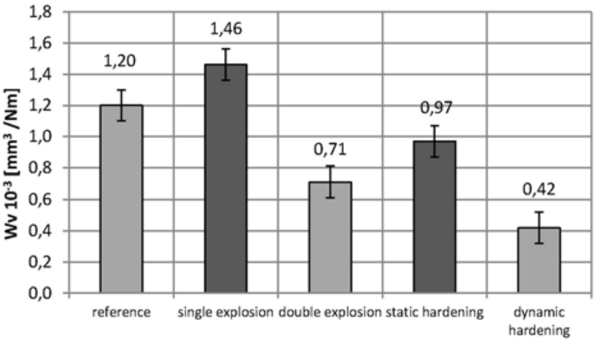

Fig. 5. **Wear index of base cast and hardened Hadfield steel**

Rys. 5. Wskaźnik zużycia objętościowego dla nieumocnionego i umocnionego staliwa Hadfielda

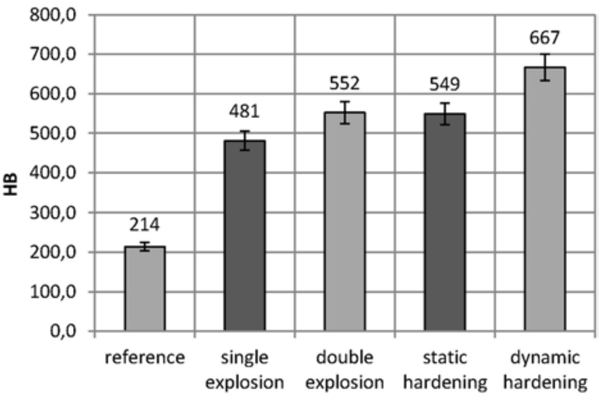

Fig. 6. **Hardness HV10 of surface layer of base and hardened Hadfield cast steel**

Rys. 6. Twardość HV10 powierzchni nieumocnionego i umocnionego staliwa Hadfielda

In the case of static burnishing, the hardness enhancement to 549 HB was similar to strengthening with a double explosion. The highest value of hardness 667HB was obtained by dynamic burnishing. It should be pointed that this value is about 3.2 times higher than it is for the raw material.

The results of indentation tests on sample cross-sections are shown in **Fig. 7**. They confirm results presented in literature **[L. 6–8]** regarding to influence of both static-rolling and explosive strengthening methods on hardness increase. The microhardness of the reference sample was 258 μHV. This is a higher value than that obtained by the macro method that is associated with a different measurement method and a lower penetration depth, although the difference of 17% is not high. All strengthening methods caused significant hardness increases of surface layers to a 1mm depth. In the case of explosive strengthening, there is no difference between one and two explosions for a distance greater than 250 μm from the surface (**Fig. 7)**; however, a higher hardness was found closer to the surface after two explosions. At a distance of 1mm from the surface, microhardness after both one and two explosions is practically the same 325 μHV; however, it is still 25% higher than for the untreated material. For static-rolling burnishing, microhardness values up to 180 μm depth are between the results found after explosive strengthening. The hardness remains constant equal to 500 μHV, which is twice as hard as the raw material, down to a depth of 320 μm, and then it decreases in similar way to explosively strengthened layers. Dynamic burnishing caused the hardness increase to 750 μHV to a depth of approximately 730 μm. Then, a slight decrease to about 680 μHV at a depth of 980 μm was measured. This indicates that dynamic burnishing is the most effective hardening method that allows obtaining a hardness 3-times higher than for the reference cast steel.

For final verification of this method for turnout frogs strengthening, research program is planned. The main aim will be the optimization of the technological parameters of dynamic burnishing and the analysis of surface fatigue under cyclic rolling contact at contact stress that corresponds to real contact of the train wheel and rail.

CONCLUSIONS

The results of mechanical and tribological confirmed the possibility of developing an alternative technology to explosive strengthening of high manganese cast steels used for the production of rail turnout elements. Dynamic hardening seems to be a very promising technology, considering the obtained high surface hardness of 667 HV10 and a hardness profile measured on sample cross-section with respect to all other tested materials. Increasing the distance from the surface to 1 mm, only a slight hardness decrease was found. Compared to other analysed strengthening technologies, the dynamic method allowed obtaining the greatest hardening depth. However, the coefficient of friction (0.89) is higher than after two explosions but smaller than for the untreated sample, the sample hardened by a single explosion and the sample subjected to static-rolling burnishing. It should be indicated that CoF was stabile during test durations. The most important parameter – the wear index – is the lowest at $0.42 \cdot 10^{-3} \frac{mm^3}{Nm}$ among all hardening methods, and 3 times lower than for the reference sample of cast steel. Results for explosive strengthening showed that two explosions provides higher hardnesses, lower wear indexes and CoF values than only one explosion. However, the thickness of the hardened layer (250 μm) is similar for one and two explosions. Obviously, further research is necessary to check the other mechanical and tribological properties, to optimize the parameters of new proposed techniques, and to obtain the most effective results.

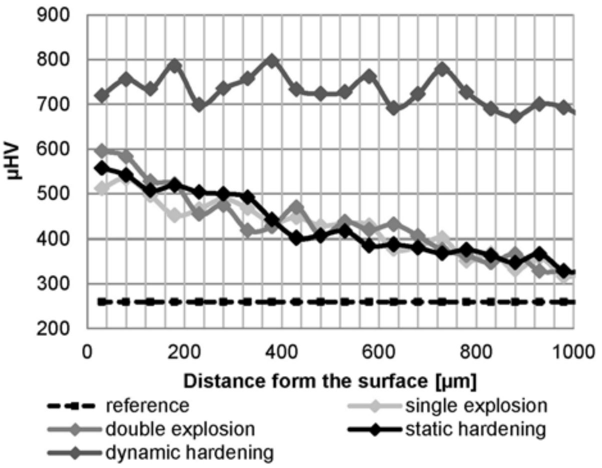

Fig. 7. Microhardness profiles of base and hardened Hadfield cast steel vs. distance from surface

Rys. 7. Rozkłady mikrotwardości od powierzchni nieumocnionego oraz umocnionego staliwa Hadfielda

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